Chapter 7:

Design & Optimization of SCL layout

7.1 General consideration

7.2 Efficiency analysis

Linac Architecture Design Choices

- Goal: object driven parameter
  beam energy, power, beam properties….

- Choice of RF structure
  cavity types, betas, no. of groups

- Choice of RF frequency
  structure, available RF power sources

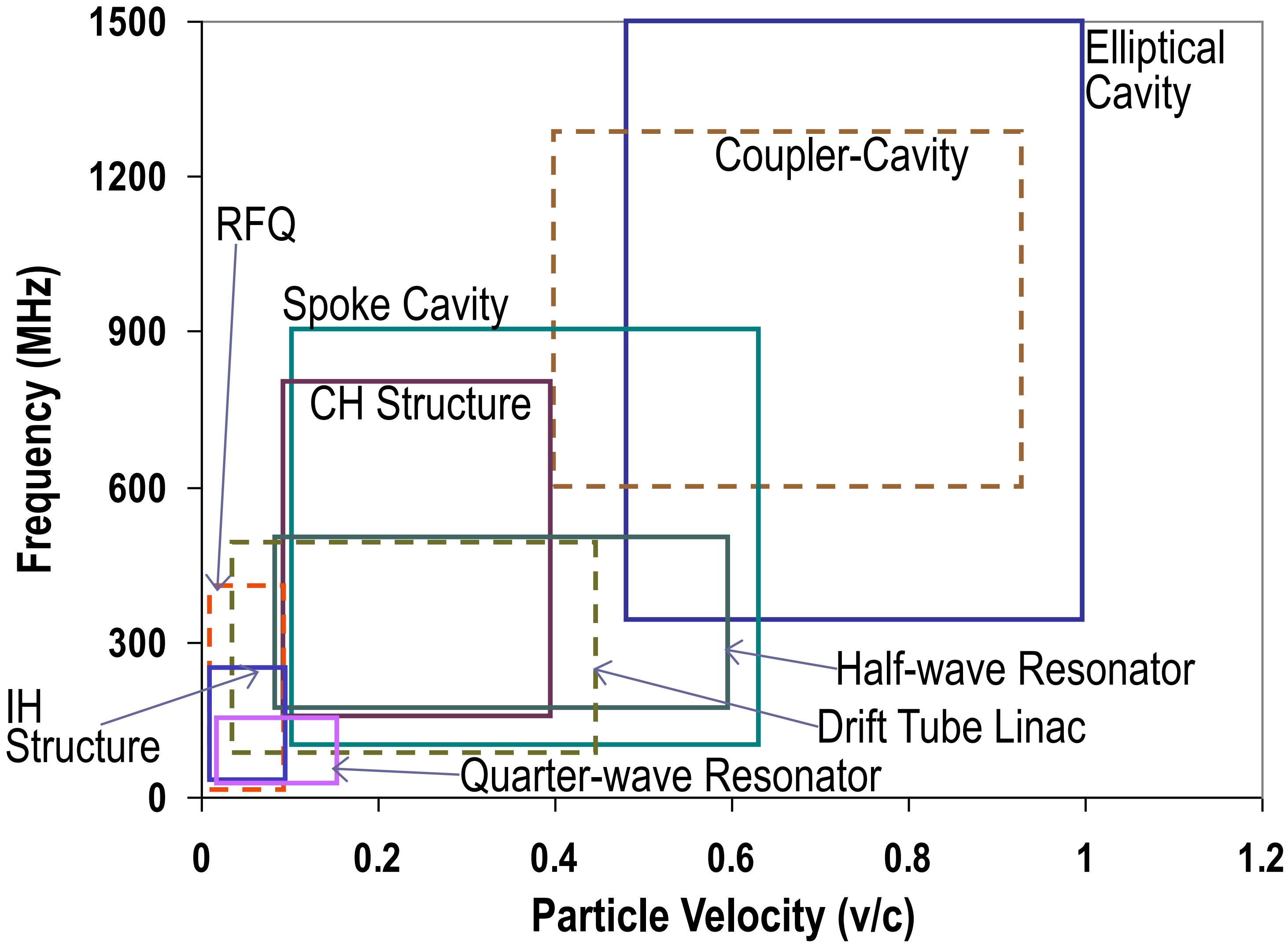
- What gradient can be reliably achieved?
  peak fields, technology

- Beam
  loss, dynamics

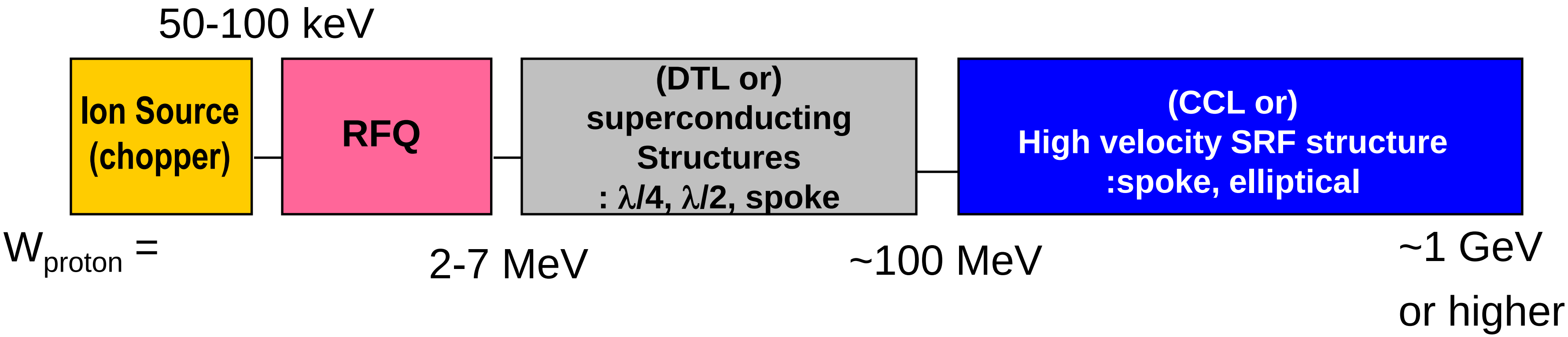
- Choice of NC/SC transition energy
  trend pushes lower

- Lattice type: solenoid or quadrupole focusing? Cold or warm magnet?
- No. of cavities/cryomodule
- Warm to cold transitions? Warm or cold instrumentation? Cryogenic segmentation: parallel cryogenic feed from a transfer line, or interconnected cryomodules?
- Operating temperature: 2K or not 2K?
- Extract Higher-Order-Mode power or not?
- Other parts/equipment availability

Plus machine specific restrictions. (schedule, cost, site-specific…)
Optimization for capital cost, operating cost, minimize risk.
Through trade-offs and lots of iterations


1500
1200
900
600
300
0
0
0.2
0.4
0.6
0.8
1
1.2
Frequency (MHz)
Particle Velocity (v/c)
Elliptical Cavity
Coupler-Cavity
RFQ
Spoke Cavity
CH Structure
Half-wave Resonator
IH Structure
Drift Tube Linac
Quarter-wave Resonator

Typical layout of Ion-Linac



50-100 keV

Ion Source (chopper)

RFQ

(DTL or) superconducting Structures : $\lambda/4$, $\lambda/2$, spoke

(CCL or) High velocity SRF structure :spoke, elliptical

W_{proton} =

2-7 MeV

~100 MeV

~1 GeV

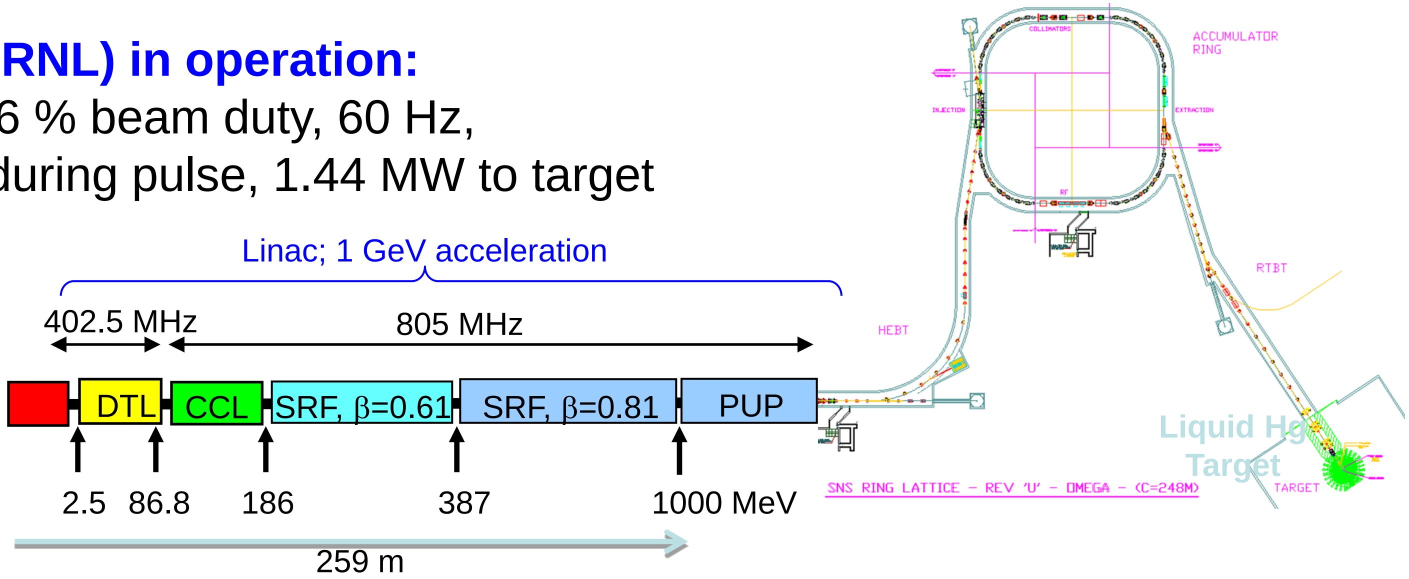
or higher

- In the SNS, CCL accelerates beam up to 186 MeV and 2 beta-sections of elliptical cavities (0.61 & 0.81) to 1 GeV (power upgrade to 1.3 GeV)

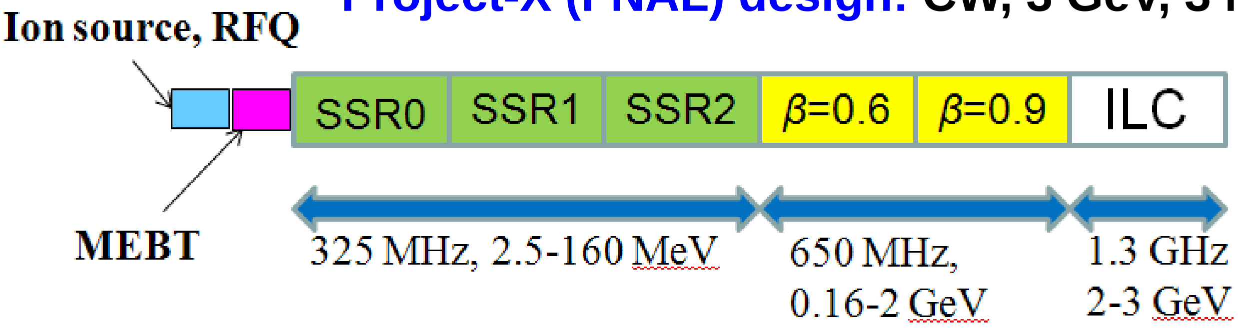
- Superconducting structures are adapted for low energy regions (=<100 MeV) in newly proposed linacs (FRIB, Project-X, ESS, …): SRF structures are expanding their applications to lower beta regions.

SNS (ORNL) in operation:

1 GeV, 6 % beam duty, 60 Hz,
26 mA during pulse, 1.44 MW to target

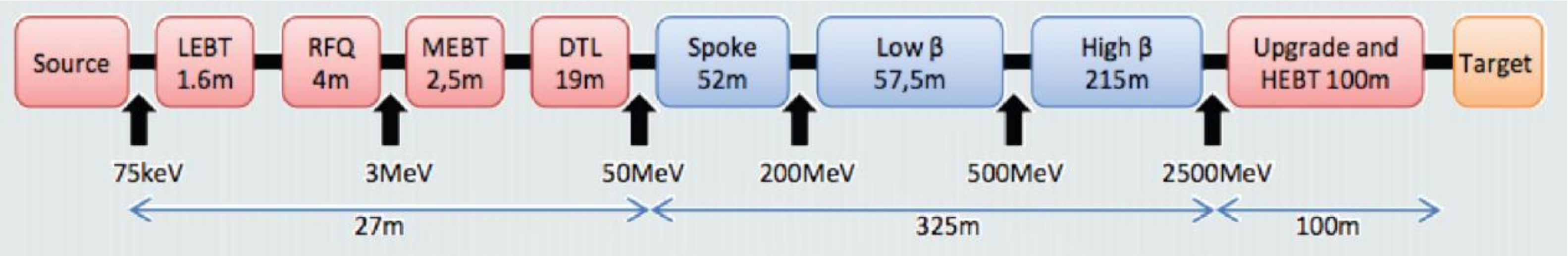


Project-X (FNAL) design: **CW, 3 GeV, 3 MW**

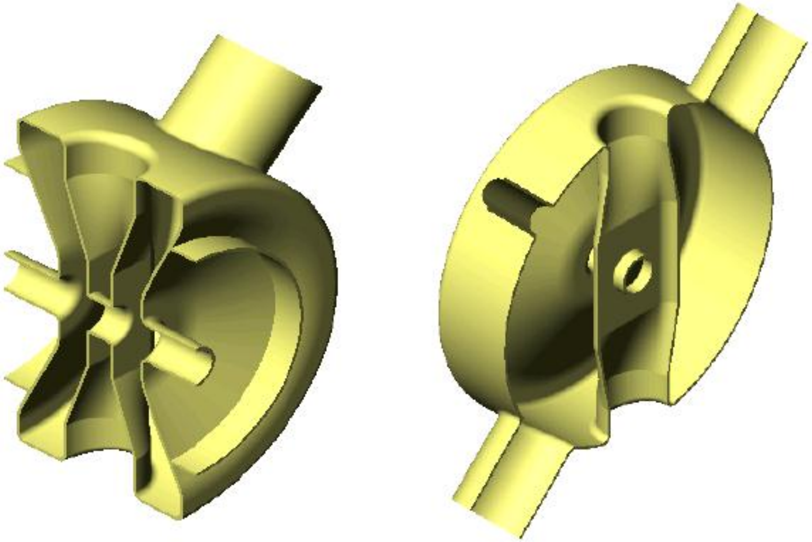


ESS (EU, Sweden) design:

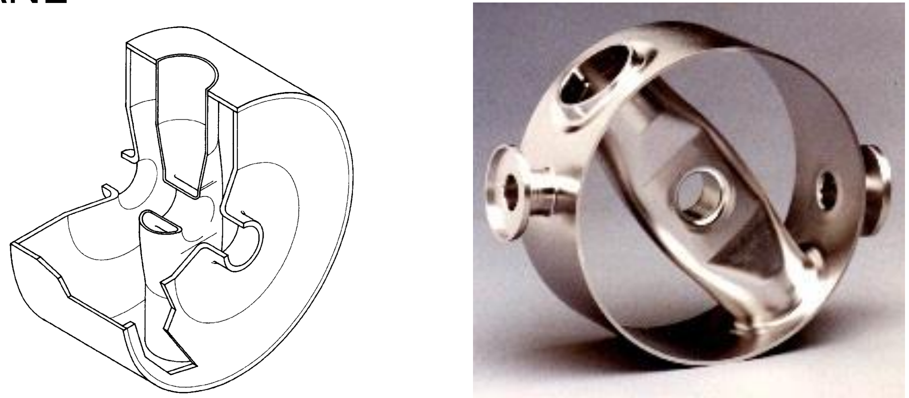
Pulsed : 2.5 GeV, 4 % beam duty, 20 Hz, 50 mA during pulse, 5 MW



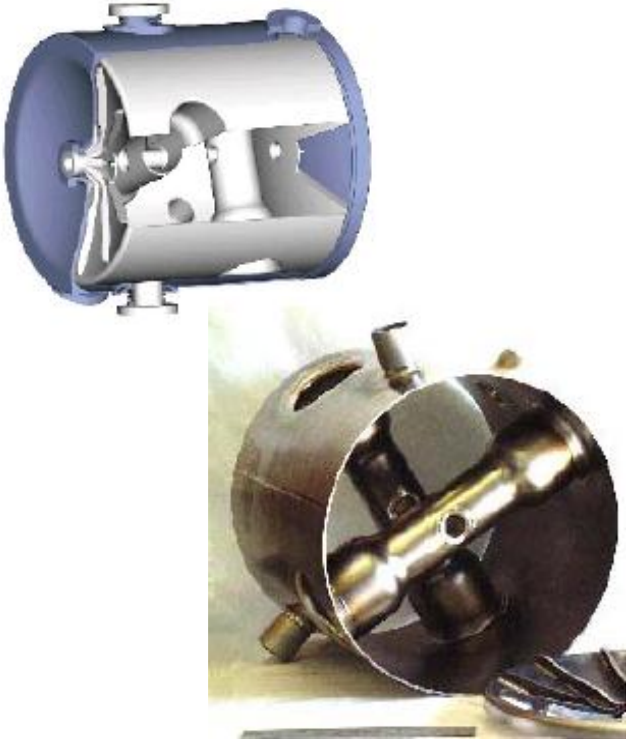
SRF structure for low & medium beta ranges



AAA/LANL, 350 MHz, β=0.175, 2-gap spoke cavity
LANL



Prototype for ion beam acceleration
850 MHz, β=0.28, 2-gap spoke cavity
JLab



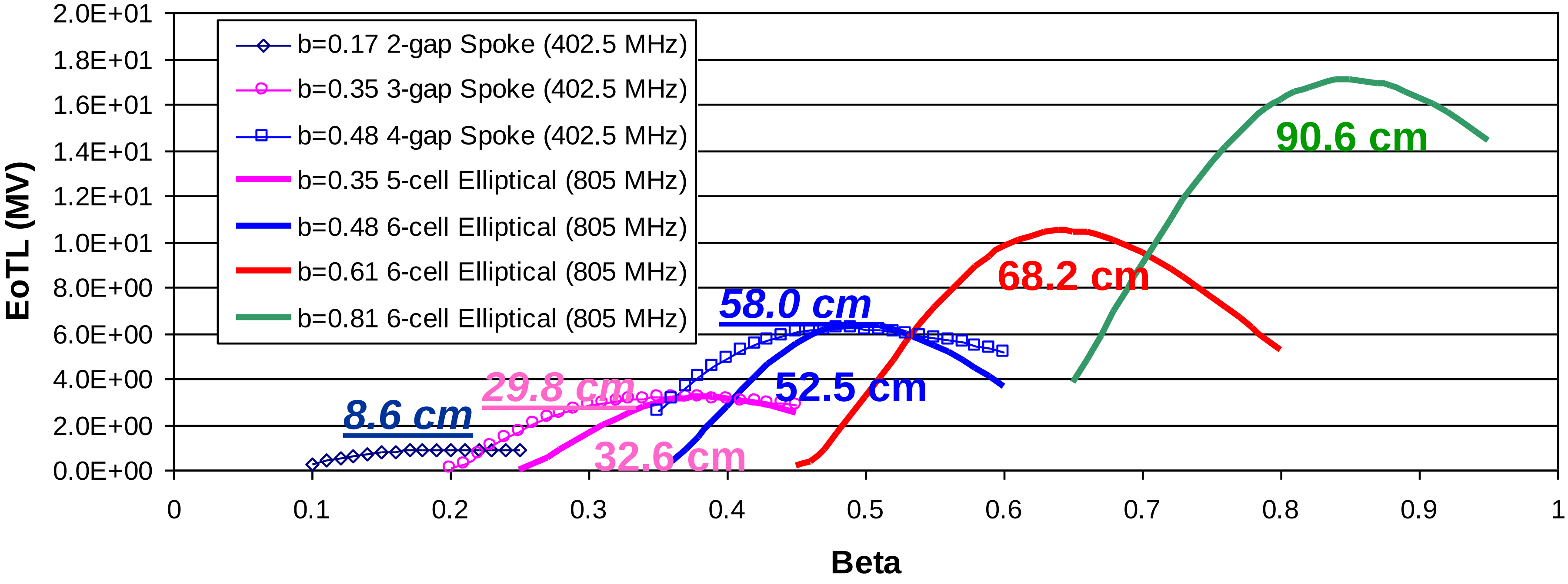
345 MHz, β=0.4,
3-gap spoke cavity
for ion beam acceleration
ANL

Comparisons of RF properties (elliptical cavity and spoke cavity)

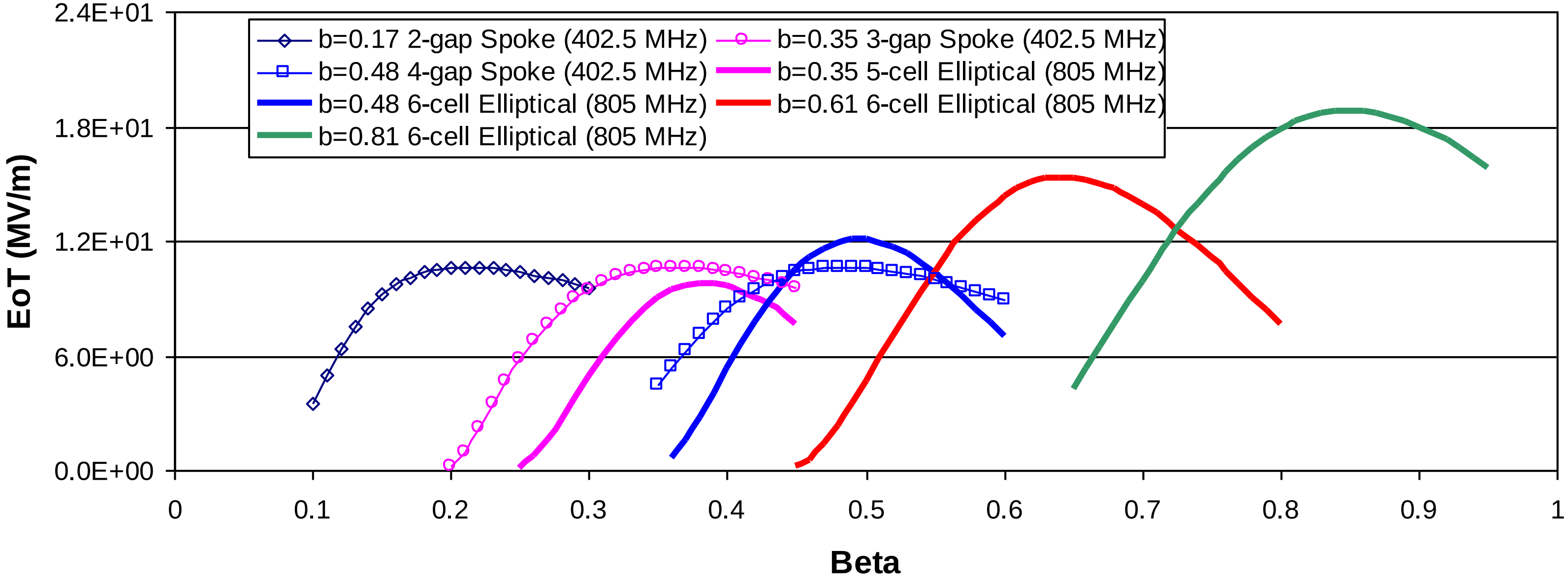
Ex)

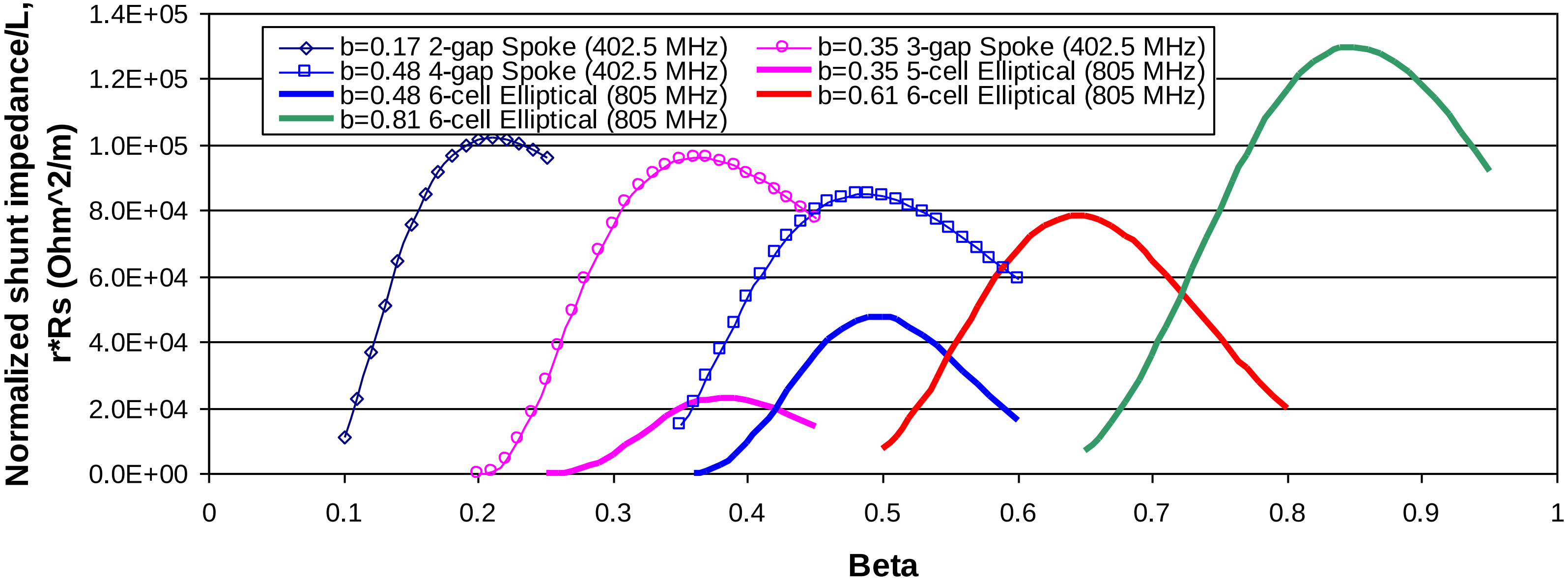
3 spoke cavities (402.5 MHz), and 4 elliptical cavities (805 MHz) optimally designed for simple RF property comparisons for proton under the same criteria: Ep~40 MV/m, Bp~85 mT.

k=1.5 % for Elliptical cavity



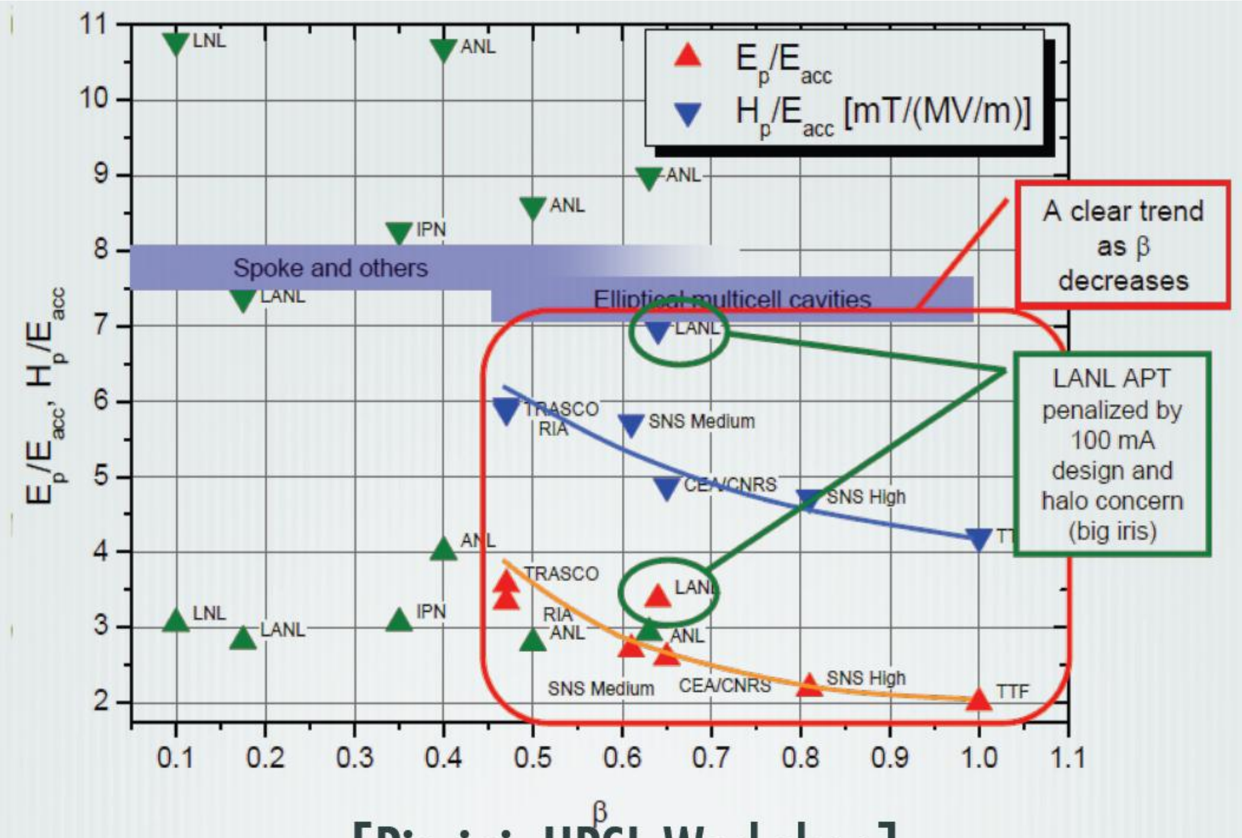
EoT & Normalized shunt impedance





General scaling references cavity parameters

Most of points in this plot: design, R&D, or prototypes
So far the SNS is the only one for proton beam in operation.



A clear trend as β decreases

LANL APT penalized by 100 mA design and halo concern (big iris)

[Pierini, HPSL Workshop]

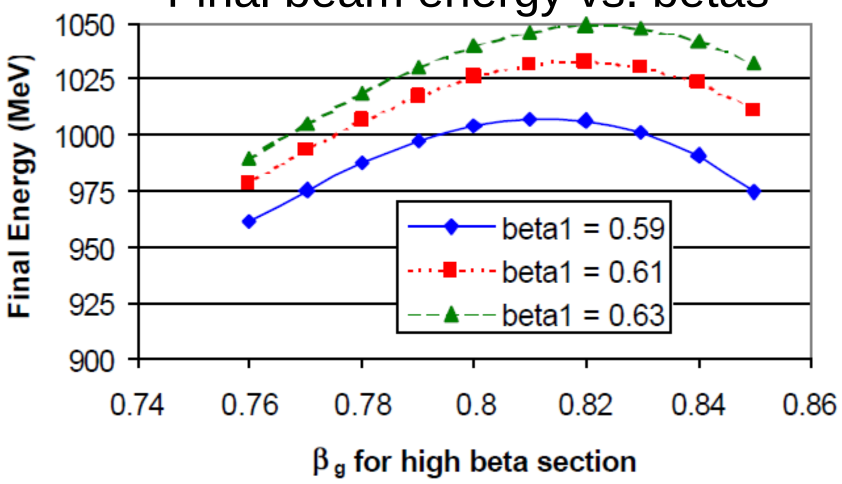
Ex. SNS SCL history and initial design concern

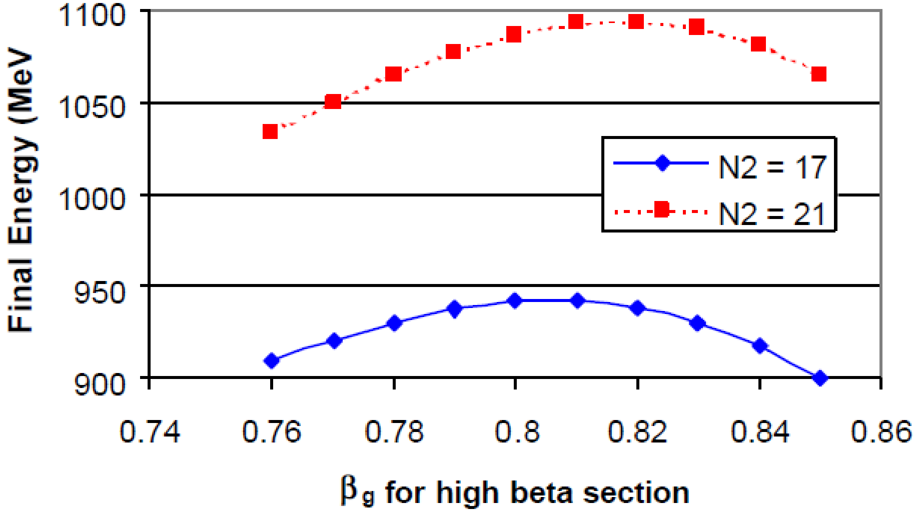
- Goal: 1GeV, pulsed, >1MW proton machine for spallation neutron source
- SNS baseline change from NC to SC in 2000, relatively late in the project
- RF frequency; followed that of the NC CCL (from LANSCE)
- Two beta groups: 0.61 and 0.81→ after CCL module 4 (186 MeV)
  - Cost, schedules for prototyping
- Beam dynamics with doublet lattice
  - 3 cavities/ medium beta cryomodule
  - 4 cavities/high beta cryomodule
- SRF Cavity designs were mainly driven by two constraints
  - Power coupler; maximum 350 kW (later increased to >550 kW)
  - Cavity peak surface field; 27.5 MV/m field emission concerns
    - Constant gradient/cavity
    - Later increase to 35 MV/m for HB cavities by adapting EP

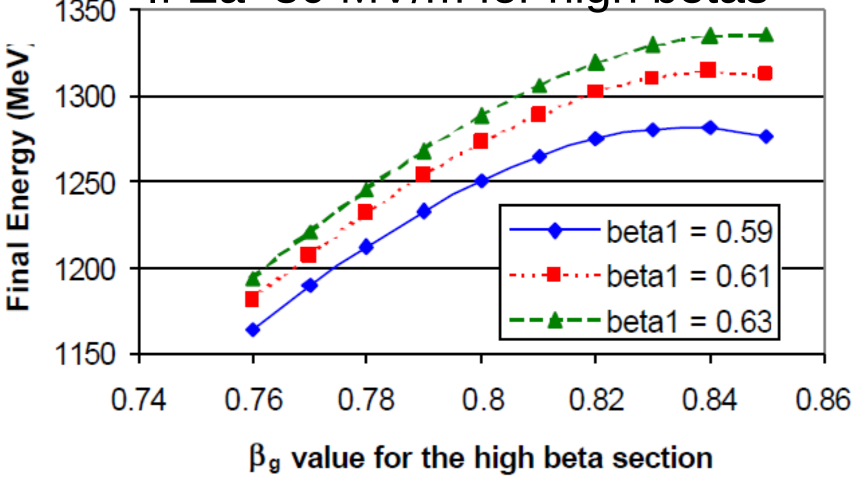
Ex. SNS SCL history and initial design concern (continued..)

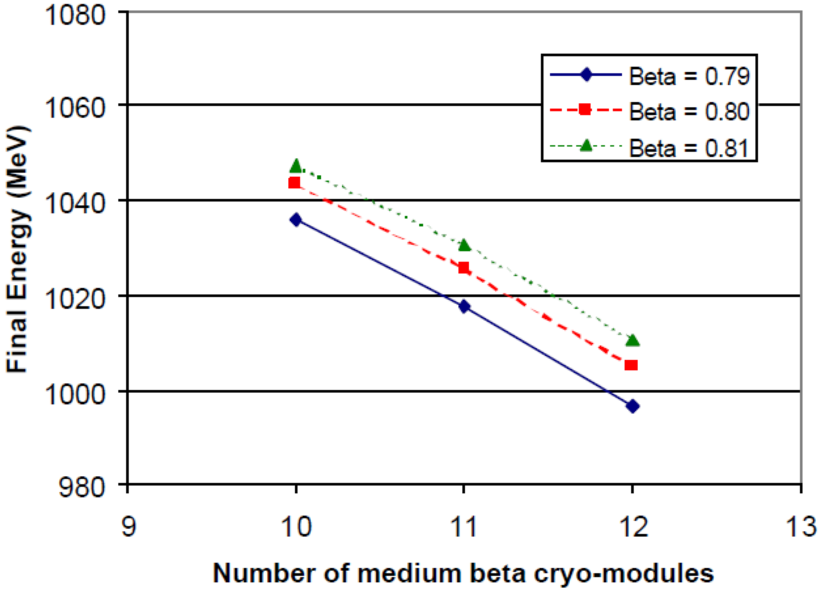
- With one FPC to cavity; HB cavity → 6 cell
- Long. Phase slip at low energy; MB cavity → 6 cell
- Power coupler; scaled from KEK 508 MHz coupler
- HOM coupler; scaled from TTF HOM coupler
- Mechanical tuner; adapted from Saclay-TTF design for TESLA cavities
- Piezo tuner; incorporated into the dead leg for possible big LFD (later on)
- Cryomodule; similar construction arrangement employed in CEBAF
- Nb material RRR>250 for cells and Reactor grade Nb for Cavity end- group
- And then usual optimization process
  - TTF, peak surface field balancing, raise the resonant mechanical frequency, LFD, HOM, etc

Ex.) some selected examples during SNS SCL layout design


Final beam energy vs. betas


If Ea=25 MV/m for high betas

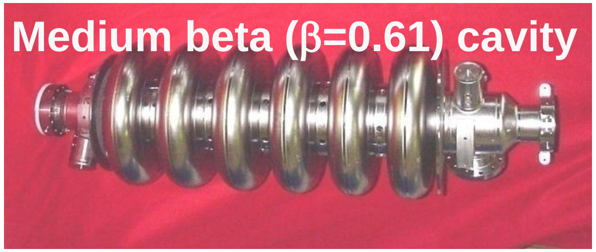

If Ea=30 MV/m for high betas



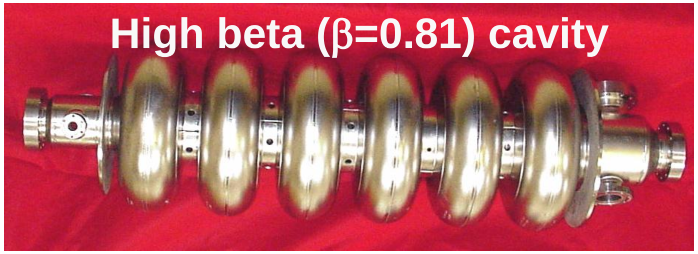
Finally SNS Cavities and Cryomodules look;

β=0.61 Specifications:
E_a=10.1 MV/m, Q_o> 5E9 at 2.1 K

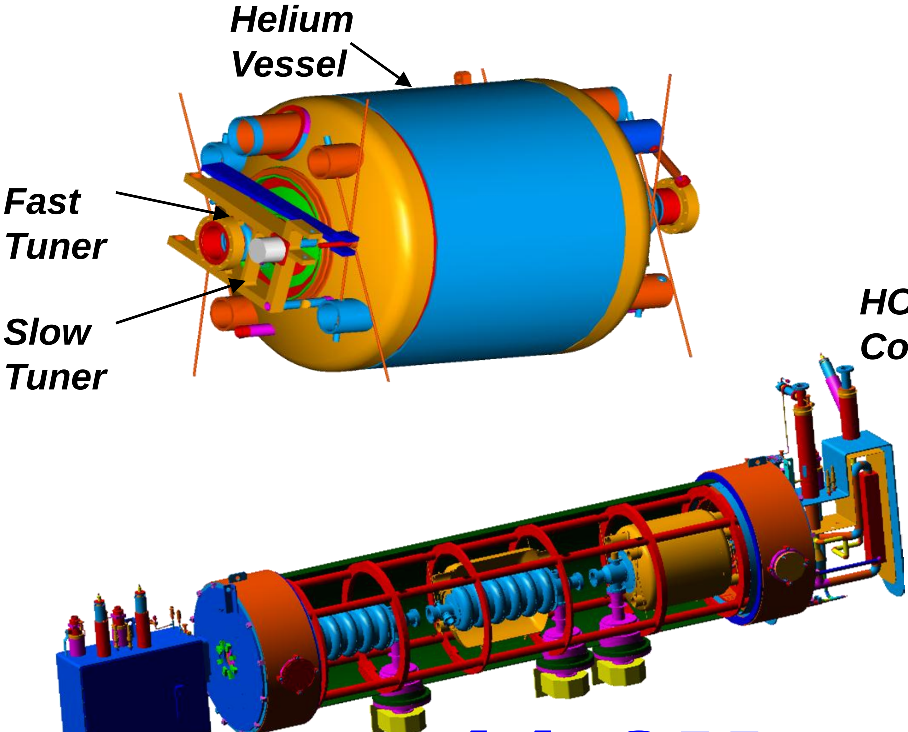
β=0.81 Specifications:
E_a=15.8 MV/m, Q_o> 5E9 at 2.1 K



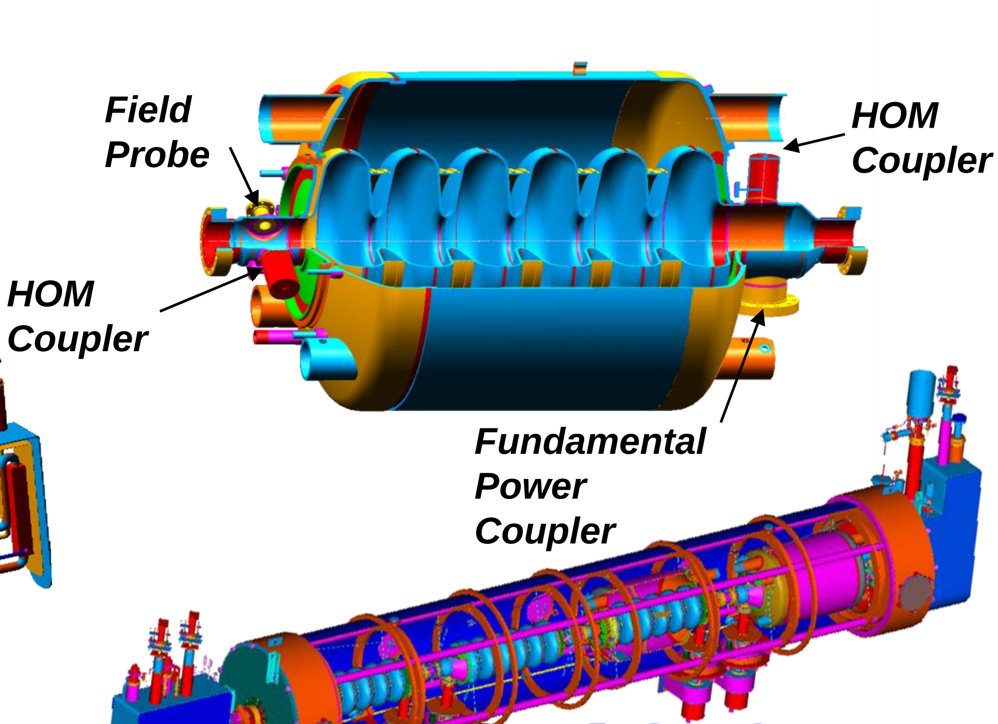
Medium beta (β=0.61) cavity



High beta (β=0.81) cavity

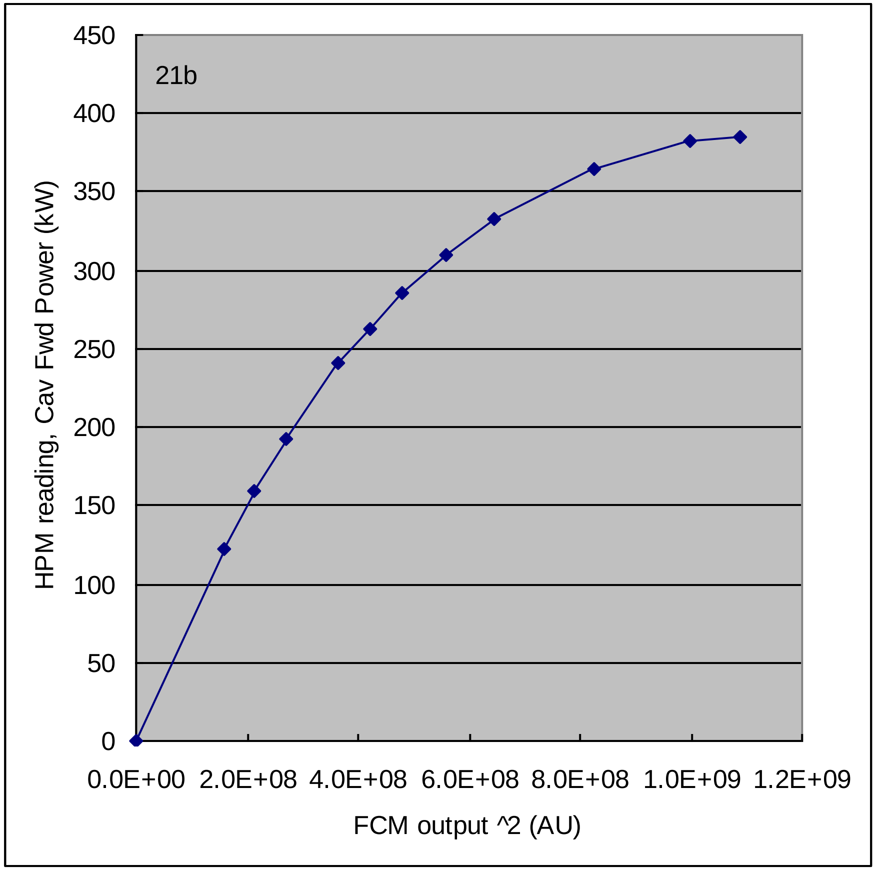


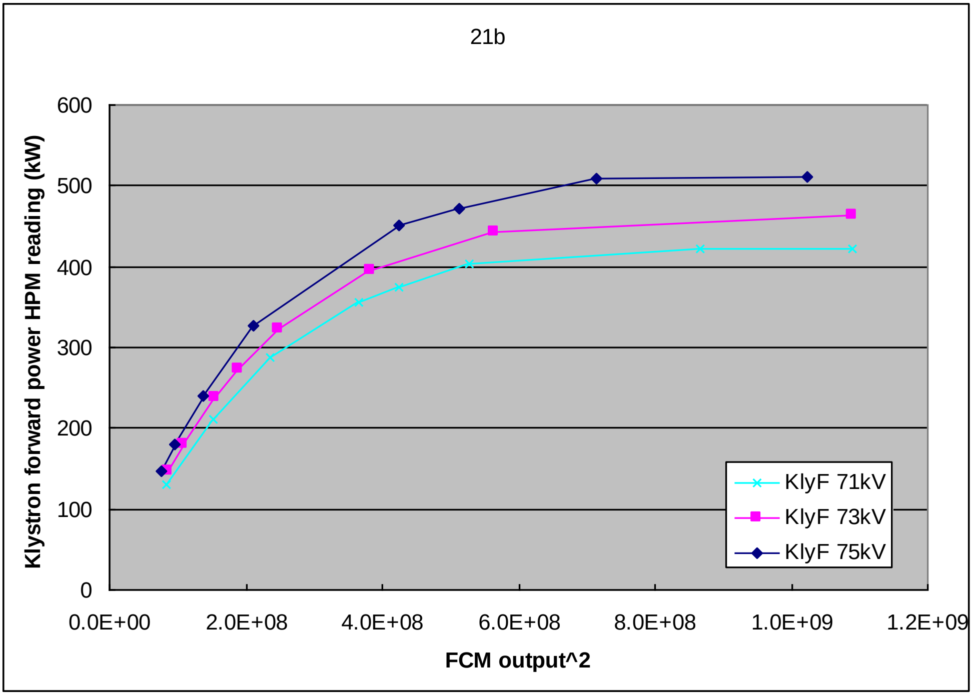
11 CMs



12 CMs

Typical RF Gain curves of klystrons:

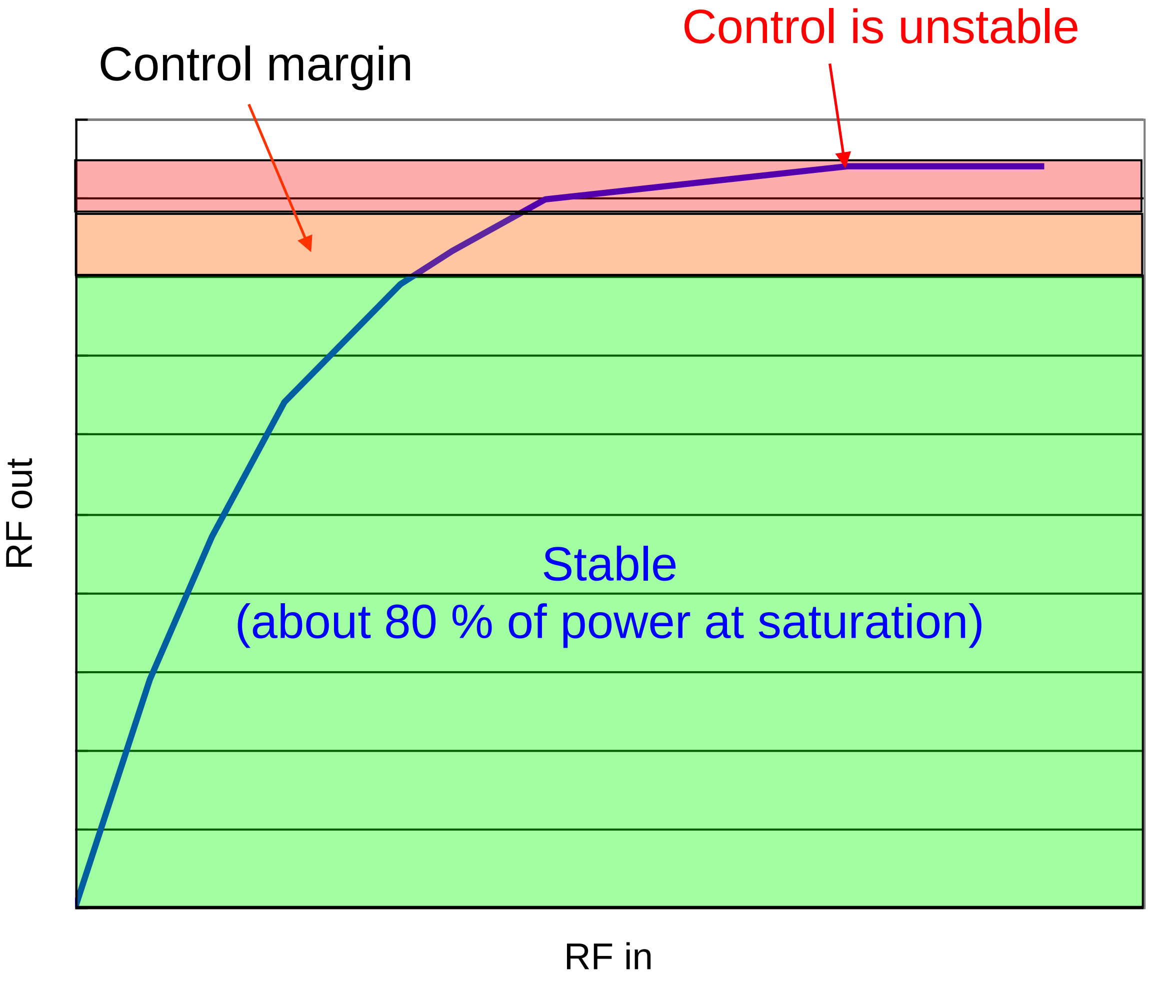


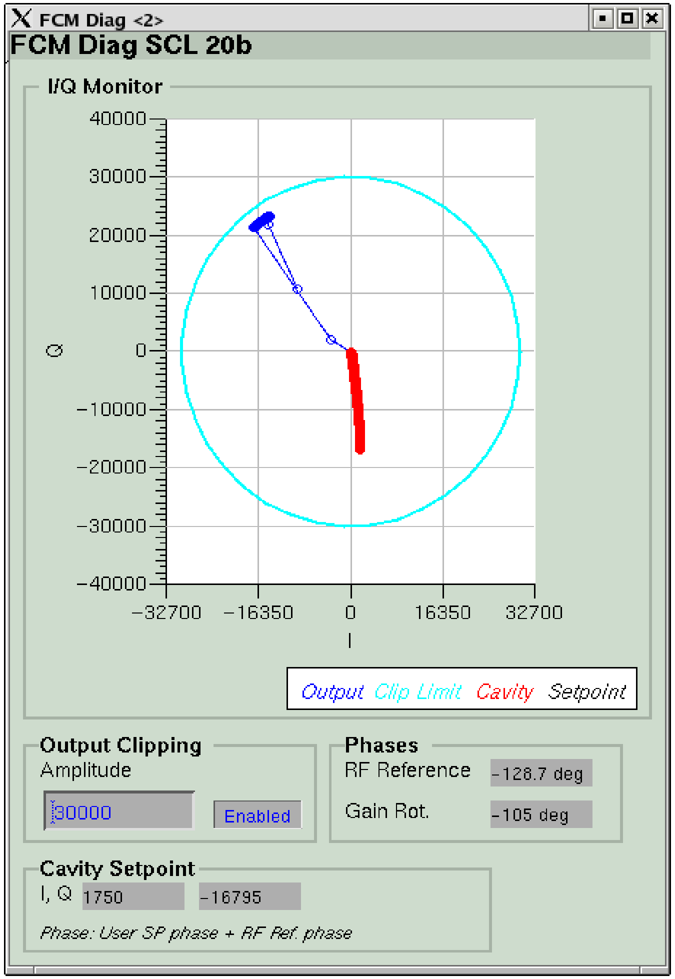


FCM digital output → amp on FCM board → solid state amp (transmitter) → klystron → **Cavity forward power**

RF Margin:

High current in pulsed operation needs more control margin.





FCM Diag SCL 20b

Output Clipping
Amplitude 30000

Phases
RF Reference −128.7 deg
Gain Rot. −105 deg

Cavity Setpoint
I, Q 1750 −16795
Phase: User SP phase + RF Ref. phase

FCM software driving

Optimization: Cryogenics side

Given the design of the cryogenic plant, the highest overall efficiency is not necessarily achieved when the nominally optimal thermodynamic conditions are reached.

Since the cryogenic plant has to run at a fixed load no matter what the actual static and dynamic loads from the cryomodules, a more efficient use of the plant would be at temperatures different from the designed ones.

In a large scale machine, optimization could save operating cost and capital cost as well.

A precise optimization is quite difficult, since some parameters are unknown. But it is always useful to understand what can affect the operating conditions.

We will use a simplified model using the SNS cavity parameters, but we will learn the about sources/consequences and general scaling.

Remind the relations and equations before..

$\eta/\eta_{ideal} = \eta_{ratio}$

$$\eta_{ideal} = \frac{T_{op}}{T_{ambient} - T_{op}}$$

$$\frac{1}{\eta} = \frac{P_{RT}}{P_{cold}}$$

For the scaling we will use the estimation from

M.A. Green, et. al, Advances in Cryogenic Engineering, Vol. 37, Feb. 1992

$\eta_{ratio} = 0.035 \, \mathrm{Ln}(P_{cold}) \tanh(T/3)$

At a given cavity structure, variables are;

R_{BCS} (T)+R_{res}

Additional load:

field emission, beam loss, thermal radiation from coupler with RF. etc

Duty

Static loss

Other Rs terms + coupler dynamic load + beam loss

Static load

Thermal load without RF and/or beam

Cryomodule with single intermediate thermal boundary at 50-70 K → typically 1-5 W/m to the primary line (2K or 4K) depending on design and module layout

Some cryomodules for 2K operation has double intermediate thermal boundaries at 4K and 50-70 K → <0.3 W/m to the primary (2K) line

ex. very large scale, low duty machine

It is more important for large scale machines at low duty factor.

Thermal load from electron activities

Field emission is especially important.

There are pretty efficient accelerations for electrons in higher beta structures.

Electrons take energy from RF and hit the surfaces in the cryomodule, which will generate radiation (x-ray) and will be thermal deposition on surfaces.

Recall equation in section 2, which is good for T<5 K for niobium.

$$R_S = R_{BCS} + R_{res} = 2\times 10^{-4}\frac{f^{2}(\mathrm{GHz})}{1.5^{2}T}\exp(-\frac{17.67}{T}) + R_{res}$$

$$R_{res}\,;1 \sim 15\,\mathrm{n}\Omega$$

Example: using SNS cavity parameters, we will do some parametric analysis. (cryo_estimation.xlsx)

Phase and Energy

DTL, CCL, etc:

Long multi-cell structure.

Structures are designed for a reference velocity profile.

Final energy is determined by the design.

Field should be large enough for synchronism.

SRF cavity:

A cavity is composed of a relatively small number of cells

Structures have a large velocity acceptance.

Structures are powered independently.

Phase and field (energy gain and reference phase) are flexible.

Final energy is flexible too up to the field level at which structures can sustain fields reliably.

Phases in elliptical cavity

Each cell amplitude and phase information are used for input values in some beam dynamic codes.

Recall the transit time factor definition in SUPERFISH manual or text books

$$T = \frac{\int_{bs}^{be} E(z)\cos\omega t\, dz - \tan\phi_s \int_{bs}^{be} E(z)\sin\omega t\, dz}{E_0 L}$$

One can set an origin arbitrary.
If an origin satisfies, → Electrical center of the gap:

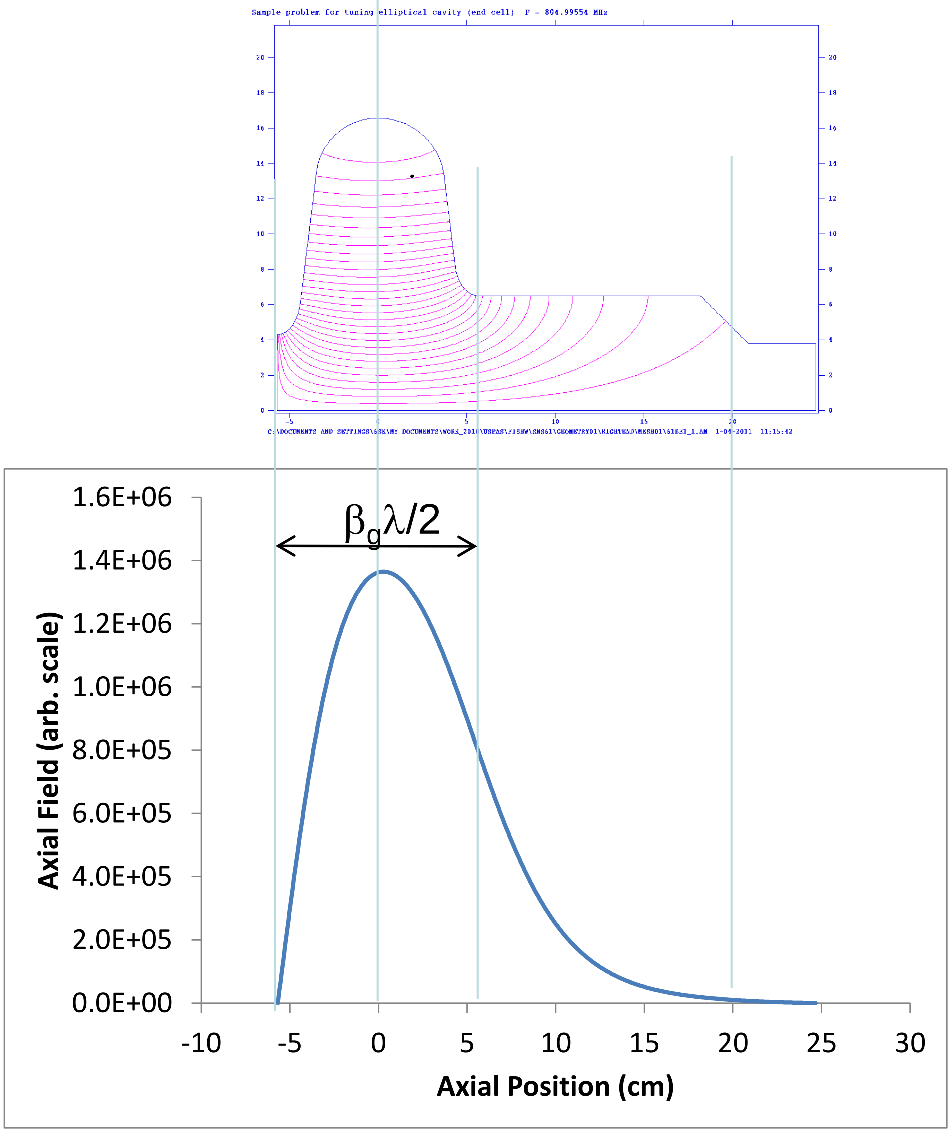
$$\int_{bs}^{0} E(z)\sin\omega t\, dz = \int_{0}^{be} E(z)\sin\omega t\, dz$$

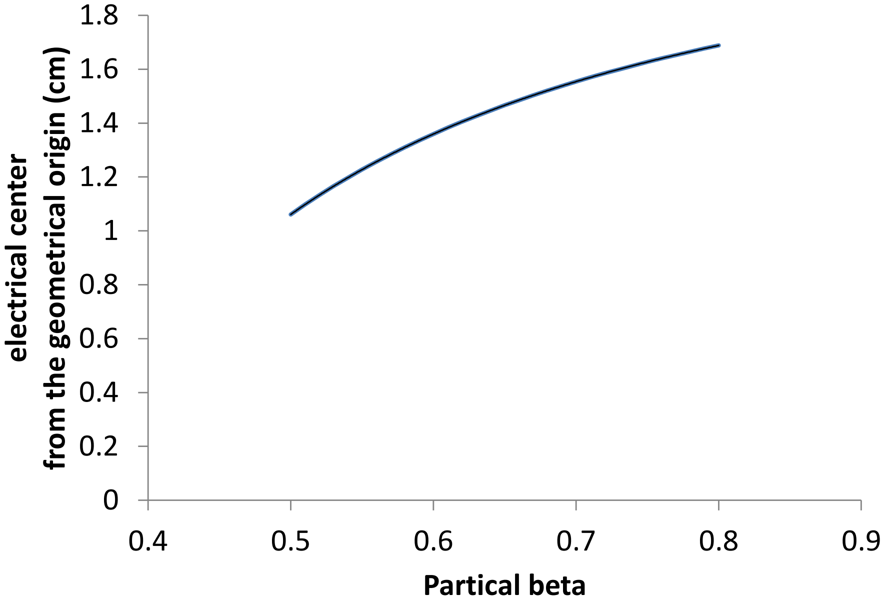
When the field is symmetry like in examples of the previous pillbox, inner cell, geometrical and electrical centers coincide. So the electrical center position is not a function of particle beta.

Ex.) SUPERFISH FILE

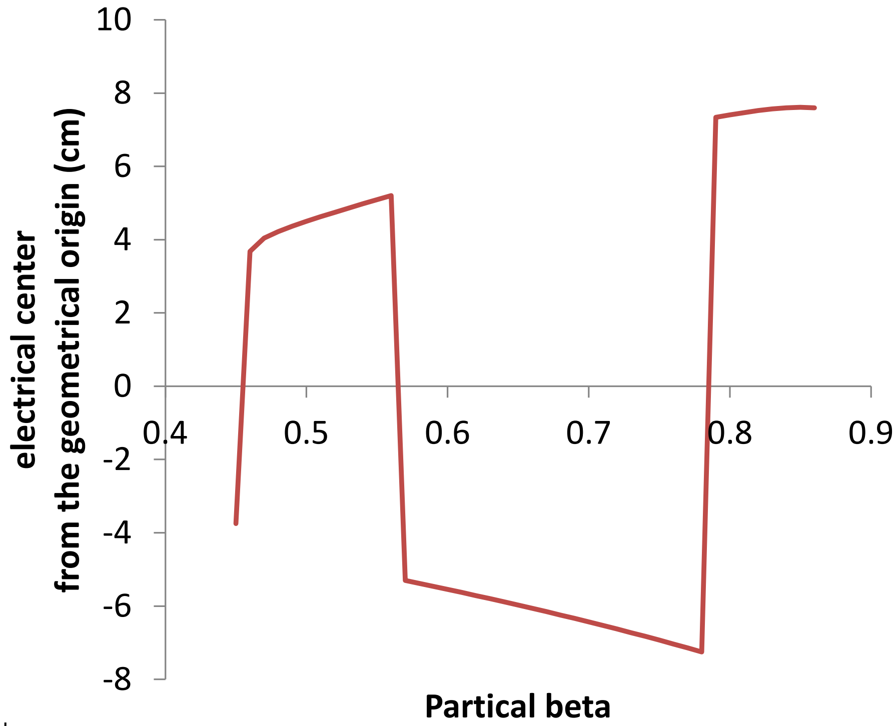
61BE1_2.AM

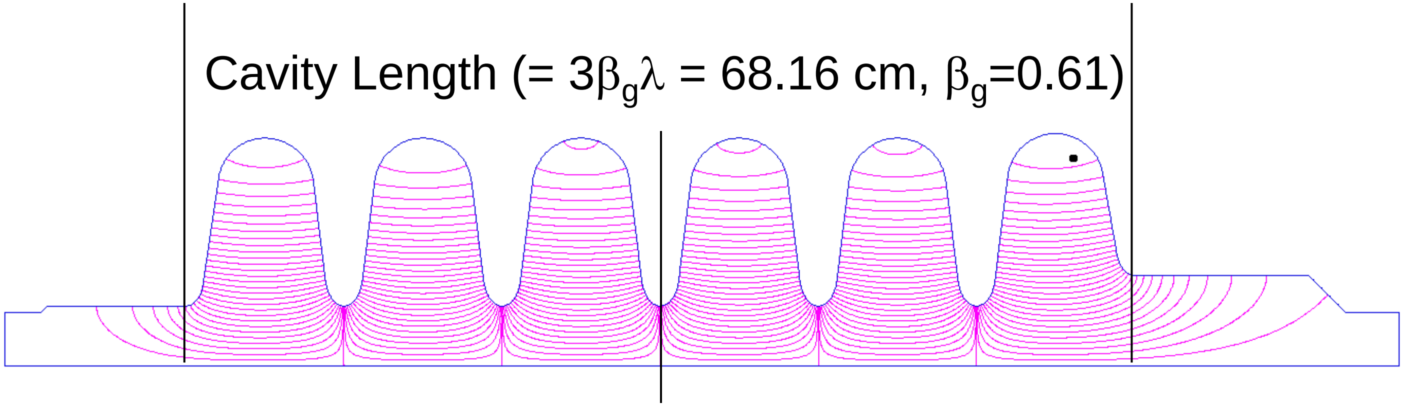
61BE1_2.SEG


Geometrical origin

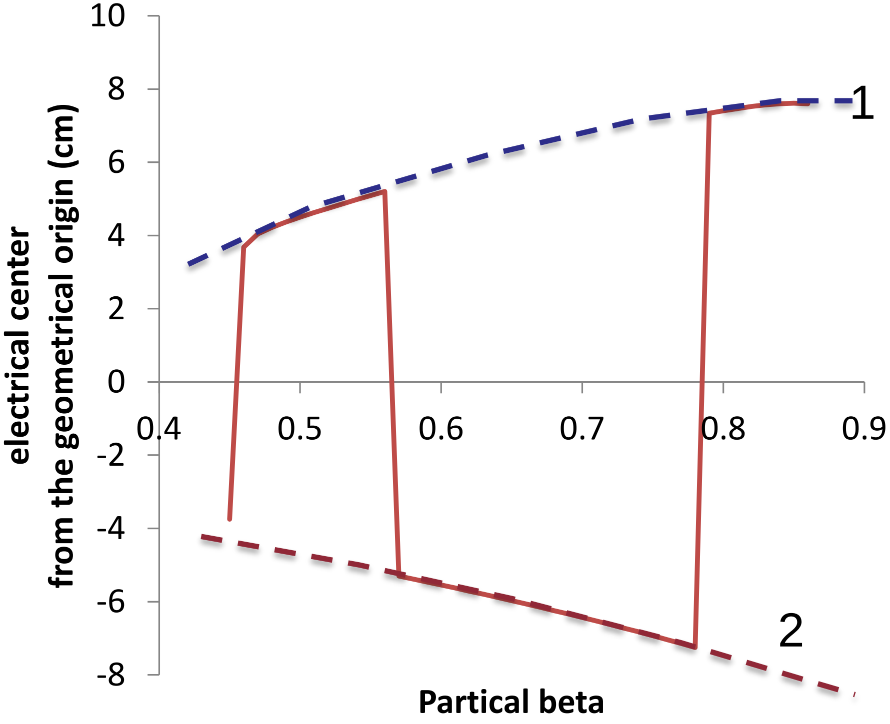


In multi-cell cavities, a particle travels for many RF cycles.
Using the (**med1.af**) for the SNS medium beta cavity, we got this result. ??





Cavity Length (= $3\beta_g\lambda$ = 68.16 cm, β_g=0.61)

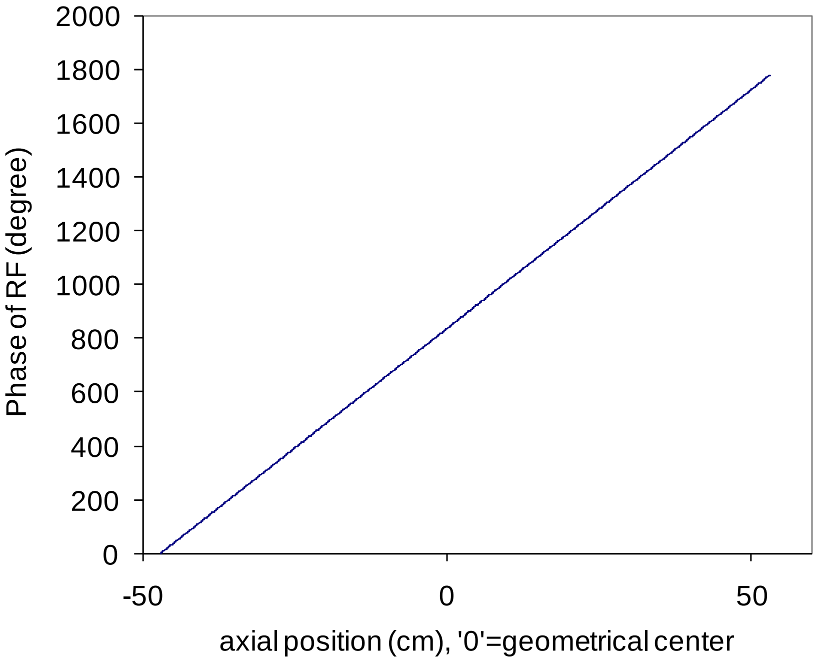


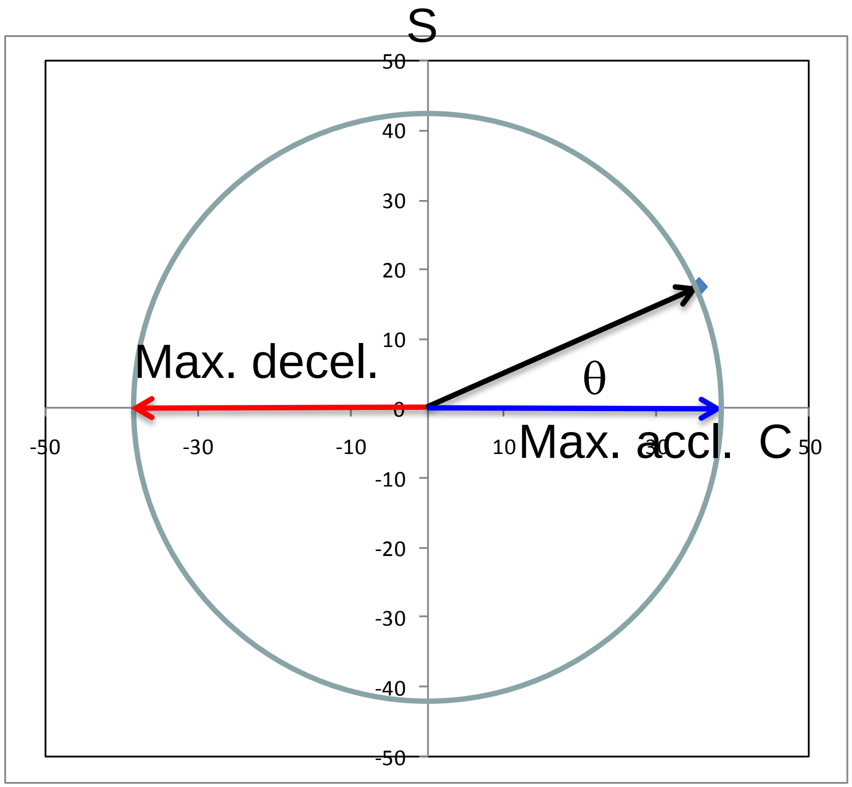
Both lines 1,2 satisfy the condition

$$\int_{bs}^{0} E(z)\sin\omega t\,dz = \int_{0}^{be} E(z)\sin\omega t\,dz$$

One corresponds max. acceleration.
The other corresponds max. deceleration.
Which one is which?

Ex.) 180-MeV particle enters the cavity boundary when RF phase is ‘0’





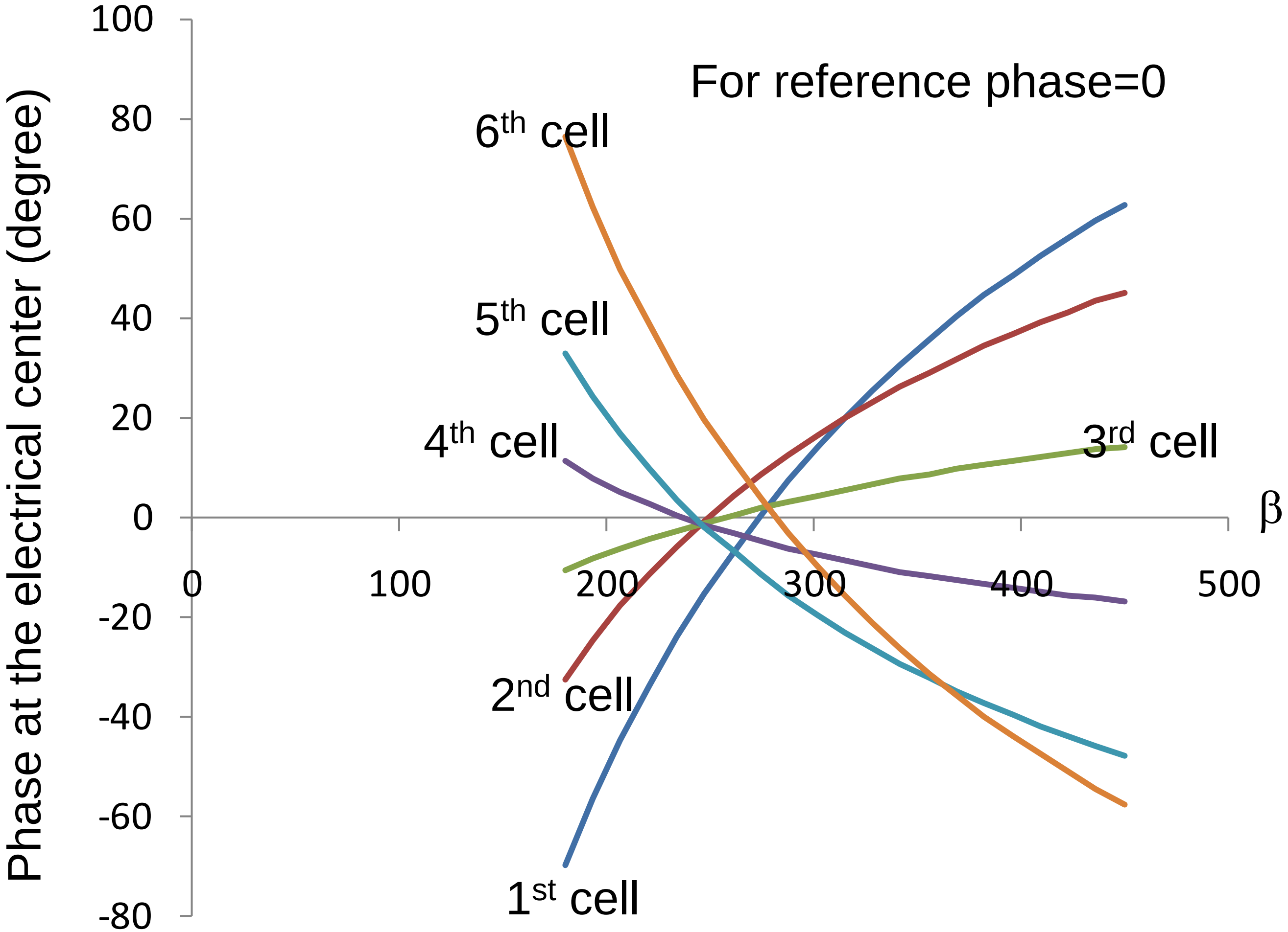
Let’s check with;

$$T = \left| \frac{\int_{bs}^{be} E(z)\cos\omega t\, dz + i\int_{bs}^{be} E(z)\sin\omega t\, dz}{E_0 L} \right| = \frac{1}{E_0 L}\left| C + iS \right|$$

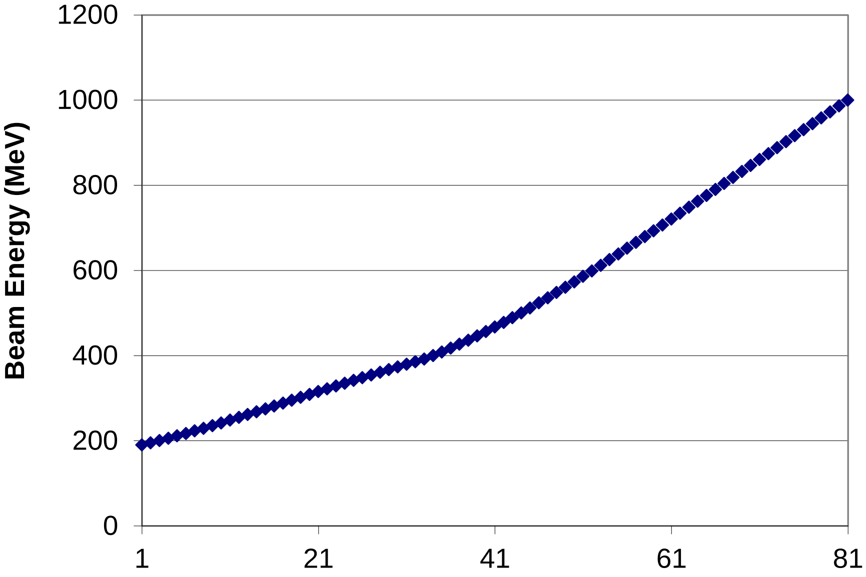
If a particle enters at -θ, maximum acceleration.
So θ+2πn (n=integer), satisfies 2 conditions→ electric centers

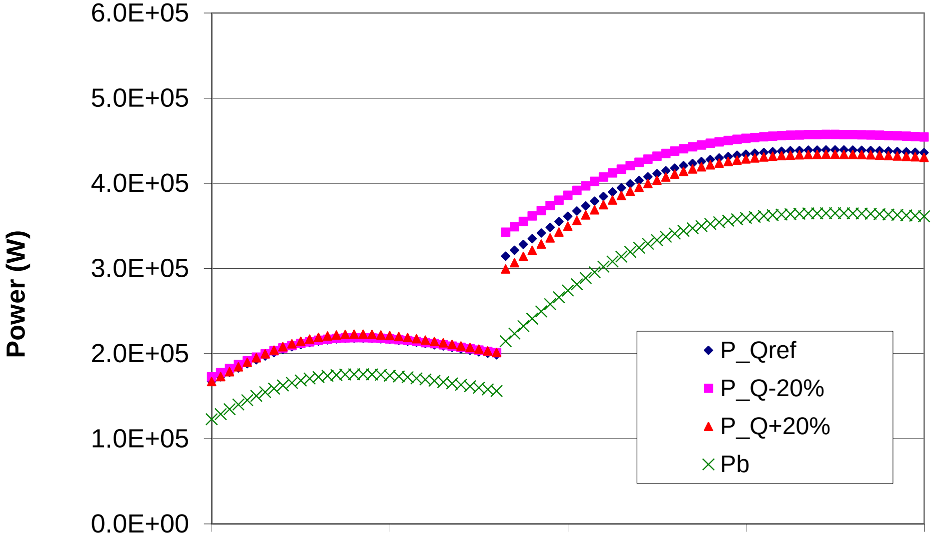
Line 1 in previous page→ maximum deceleration

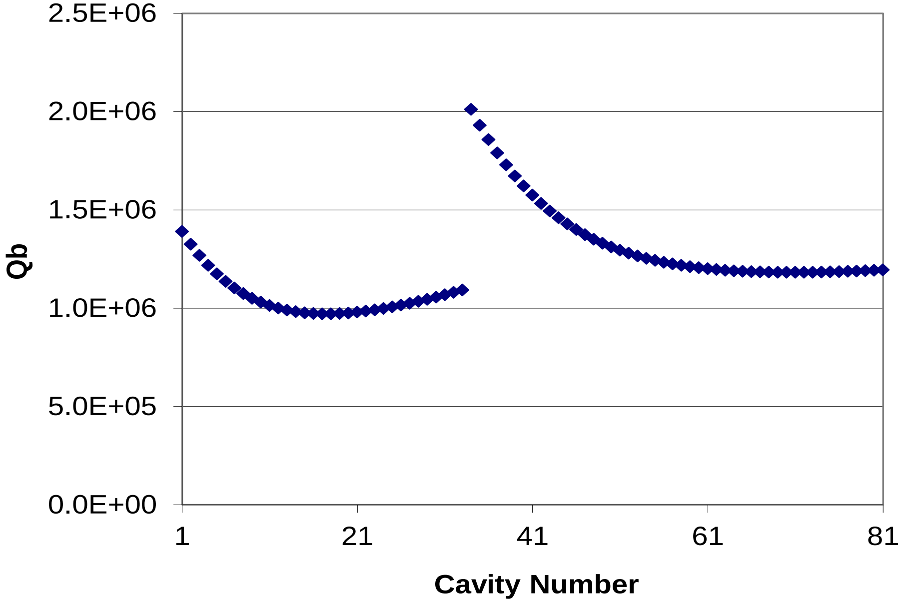
Line 2→ maximum acceleration. This should be the reference for phases of each cell.

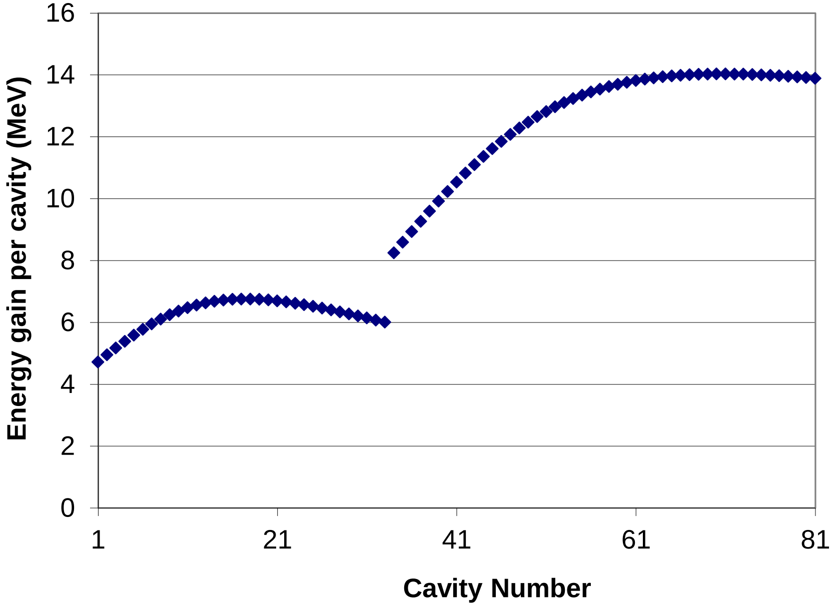


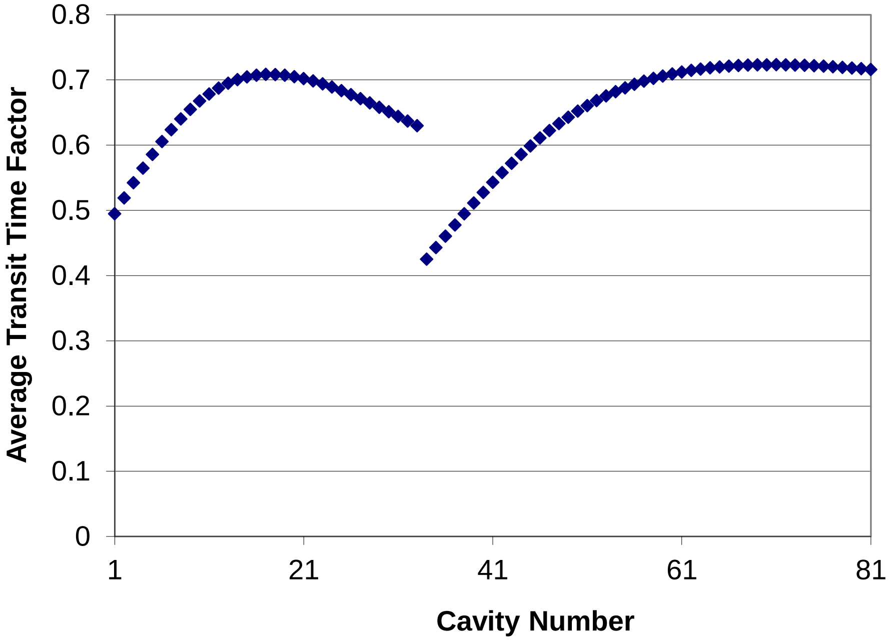
Ex.) We can develop a spread sheet using what we exercised about Energy gain, RF needed, Qex variations, detuning, etc. (energy_rf_power_linac.xls)

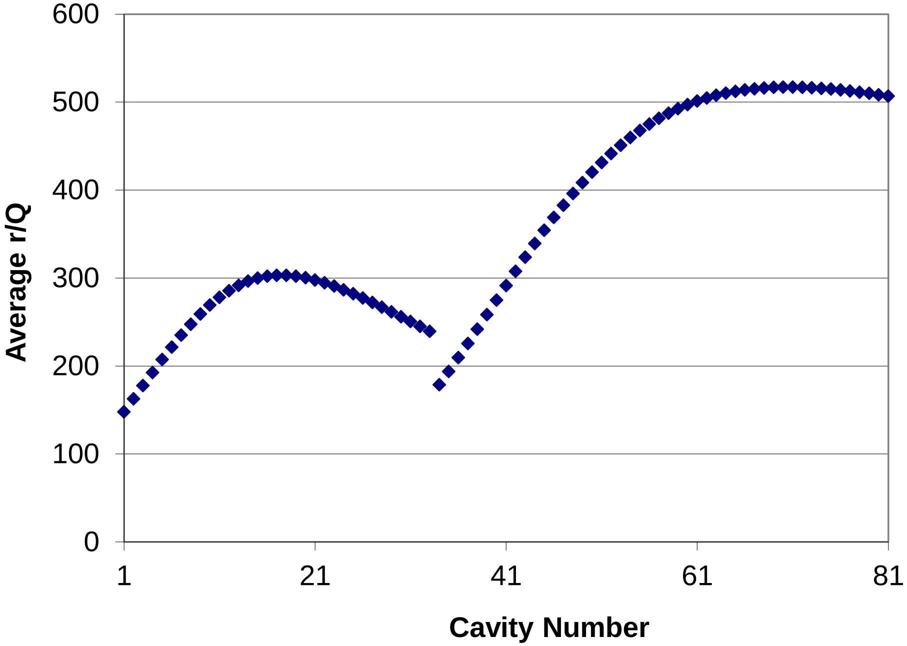


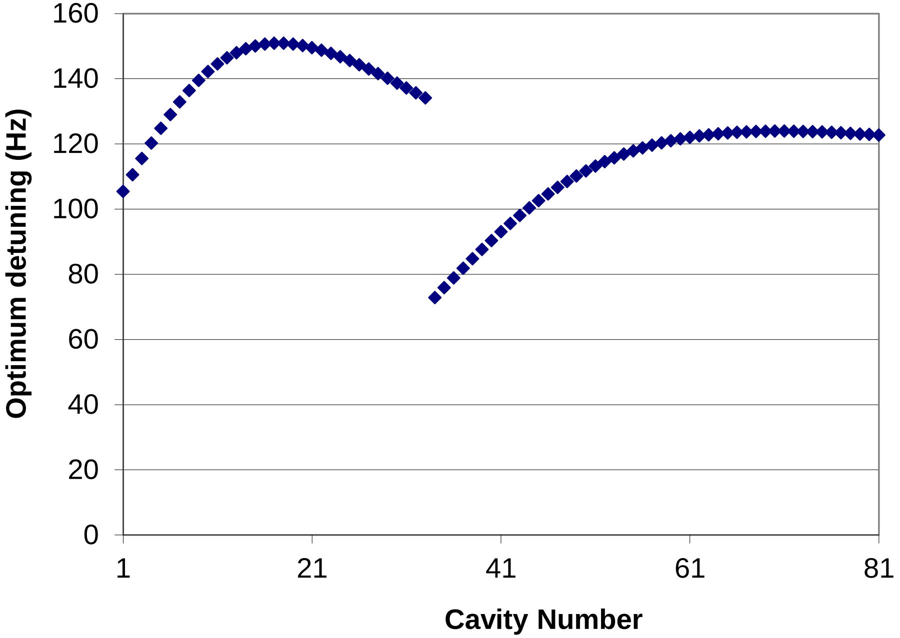







Average Transit Time Factor
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
21
41
61
81
Cavity Number


Average r/Q
600
500
400
300
200
100
0
1
21
41
61
81
Cavity Number


Optimum detuning (Hz)
160
140
120
100
80
60
40
20
0
1
21
41
61
81
Cavity Number